Competing in Engineering Design – the Role of Virtual Product Creation

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Abstract
Product creation is facing the next level of fundamental changes. Global demands are growing substantially to achieve energy efficient and sustainable value creation networks for products, production and services without compromising traditional success factors such as time to market, cost and quality. To stay competitive within such an environment development partners in industry and public sectors will require new interplay solutions for engineering design execution, domain knowledge representation, expert competence utilization and digital assistance systems. This scenario offers the chance for virtual production creation solutions to become critical for the future by offering unique engineering capabilities which have not yet explored or deployed. The paper investigates key elements of modern virtual product creation – such as agile process execution, functional product modeling and context appropriate information management – towards their competitive role in satisfying increasing numbers of product requirements, in delivering robust systems integration and in ensuring true sustainable product lifecycle solutions.

Keywords:
Virtual Product Creation, engineering design, digital technologies, information and competence management, sustainability, systems integration, process execution

1 INTRODUCTION AND MOTIVATION

Competition in Engineering Design is characterized by execution actors (designers, engineers, OEMs, suppliers, engineering service providers etc.), by technical targets and economic factors within the field of application and by higher level needs of global & regional environments and social equity. In addition, engineering design competition is influenced by implicit aspects such as general or published knowledge of an industry branch or a technical domain and special competence set-ups in enterprise environments and project teams. Each one of the above elements can lead to distinct differences in approach, operation and technology support (both physical and digital). Three fundamental aspects are laid in this paper as drivers for the benchmark criteria which then are used to assess the role of virtual product creation within engineering design competition.

The first aspect deals with the question *"what is the subject area of the activity engineering design?"*. Competition in designing a special type of product, machine, facility or service is characterized by the industry branch and oftentimes by its specific implicit design behaviors and practices: The development of an aircraft is organized in functional systems engineering activities in order to achieve best possible flight operation attributes and lifetime characteristics (weight, load capacity, fuel consumption, system robustness, safety redundancy, operating cost). The development of a fixture for an automotive welding station, however, does focus on design modularization and tool standards to enable a high chance of reuse across plants and assembly lines. These opposite examples indicate that different types of knowledge, engineering collaboration and virtual product creation technologies will serve as competing factors amongst the key development partners.

The second aspect of competition is all about *"how engineering design is executed"* and *"which main activities are associated to the design execution factory"*. The execution of engineering design within industry uses principle elements of the traditional design methodologies (e.g. VDI 2221 or Pahl/Beitz, see [1] [2]), but in the majority of the cases it does not follow them systematically. The reasons are manifold:

1. Most of the companies have not been active during the last years in using function structures to come to new design principles. The need for more intelligent products and combined systems with mechanical components, electronic and electrical modules as well as control-loop based software enablers, however, will raise the importance of function oriented design.
2. The traditional design methodologies have not taken into active consideration the complexity of products and the specific technical challenges of systems integration and verification.
3. The use of virtual product creation solutions including related processes, methods, models, tools and information standards was not yet part of engineering design when those design methodologies have been developed.

The V-model of systems engineering is another very popular development guideline and is used in most of the industry branches. For many development tasks the consistent application of the V-model is limited, too, due to problems in finding objective criteria to conduct target cascading from the entire product function down to system, sub-system and component property / attribute levels. Product and systems integration as indicated on the right branch of the V-model is also missing consistent mapping to requirements, to target cascading and to complex parameter relations of mechanical systems, electronic modules and (control) software.

Due to the nature of technical complexity engineering design activities involve many experts from different domains. A typical pragmatic approach is to connect and "integrate" those expert activities with the help of company specific development milestone charts. Project Managers with limited capabilities in technical design and validation activities serve as gatekeepers to fulfill metric based milestone deliverables. Project reviews with stakeholders often replace proper expert design reviews and serve as a control unit for turbulent engineering design execution.

In addition, engineers and designers have difficulties to cope with information complexity, PLM technologies and virtual product creation skill needs. Hence, robustness of engineering design and design efficiency suffer.

The third aspect deals with the question of *"who are the competitors?"*. Unlike schoolbook scenarios which put a single designer into the center of activity the challenge of today's engineering design competition is characterized by the following facts:

- Significant "time to market reductions" have enforced a separation of design responsibilities amongst bigger teams of design experts executing design tasks in parallel.
- The official responsibility split between OEMs, suppliers and engineering service providers require a high number of solid interface agreements.
- The provision of project resources as "warm bodies" which can be leased like a commodity on the market oftentimes conflicts with the need to develop competencies and critical development skills mid and long term.

The above described aspects of competition in engineering design lead to another key question: Can information technology help (or not) to overcome turbulent factors of competition in engineering design? If yes, which key factors are important and how can virtual product creation enable companies to acquire critical advantage in executing engineering design? The following sections will, therefore, investigate those questions in more detail as they are part of the research at the Chair of Industrial Information Technology at the Berlin Institute of Technology and at the division of Virtual Product Creation of the Fraunhofer Institute of Production Facilities and Engineering Design in Berlin.

2 COMPETITION IN ENGINEERING DESIGN – OVERVIEW, DRIVERS AND DEMANDS

Engineering Design serves as fundamental discipline to deliver appropriate design models and descriptions in order to

- meet a high number of product requirements,
- to enable robust manufacturing with high quality,
- to deliver sound profits on competitive markets,
- fulfill customer expectations during use,
- and to enable a sustainable future.

The above mentioned principle drivers for engineering design have to interact with the three fundamental aspects of competition in engineering design, as described in the previous section:

- What is the subject area of the activity engineering design?
- How is engineering design executed and which main activities are associated to the design execution factory?
- Who are the competitors in engineering design?

The authors of the paper have conducted research in order to find out which benchmark criteria might exist to clarify the question to which extend IT technologies and virtual product creation solutions can positively influence the three aspects of engineering design competition. The following eight benchmark criteria have been selected after having analyzed megatrends around the three competition aspects and the bigger product creation needs for the future. They will serve as benchmark criteria (bmc) set in the following sections:

1. *Avoidance of physical prototypes*
   In order to reduce energy and material consumption and to avoid unnecessary pollution such as carbon dioxide during the product creation phase physical prototypes should be reduced to the minimum or should be eliminated at all ("0-prototype target"). This target points directly an increase of analytical and virtual engineering capabilities.
2. *Offering of task and context oriented information and knowledge*
   Future demands for sustainable products which are in harmony with society and environmental needs require the active interpretation of an increasing number of linked information sets. Today, development engineers are already exhausted and overwhelmed in using loosely coupled information databases for engineering reasoning. This stress will become worse unless better ways can be delivered for information offering, maintenance and active use.
3. *Ensuring best suitable collaboration (incl. cultures and individual characters)*
   Product creation activities meanwhile have to rely on expert networks and dispersed project teams around the globe. Different languages, cultures and individual education background as well as multiple approaches for design engineering make it difficult to keep the focus on development project time and content targets. In addition, today's collaboration methodologies have not yet proven to deliver intelligent and clever solutions to the theoretical potential of those teams. The question remains what might be achievable via best possible collaboration.
4. *Enabling robust and transparent decision making*

   Simultaneous and cross-enterprise development processes need constant operational and milestone oriented decision making. Still today, the disciplines of Project Management and Engineering Design do not follow the same conceptual thinking. As a consequence, project and engineering progression oftentimes are not in synchronization and make robust decision making impossible. As a result major technical compromises are accepted in order to deliver projects in time and due to missing decision transparency lessons learned are not possible.
5. *Provision of a creative, individual adaptable and intuitive working environment*
   Human beings remain the most valuable asset in agile and precise engineering execution. The early engagement with non physical artefacts of future product does require new ways of work places ("new generation of work desk laboratories"). Creativity zones will play a more important role if new levels of intelligent products need to be achieved.
6. *Delivering extended lifecycle views*
   In the beginning of the 21st century it is no longer sufficient to concentrate on the production and

use of products and to leave out subsequent life cycles such as MRO and end of life recycling. Even 2nd cycle product planning and verification methods will become important.

7. *Steady maintenance and extension of competence*
   School book knowledge and job experience are no longer sufficient to meet future design engineering skill requirements. New levels of knowledge capture, consistent use and rapid innovation need to be explored to allow for future generation systems engineering and related competence networks.
8. *Product Creation Process Planning and Adaptation*
   Process competence is one of the key competitive factors and core competence of industrial companies. Beyond general guidelines and high level milestone maps there is almost no explicit representation of product creation processes available. Process models and associated target oriented deployment are highly desired to analyze and improve engineering design systematically.

3 VIRTUAL PROUCT CREATION (VPC) SOLUTIONS (PROCESS, METHODS, TOOLS) TO SUPPORT COMPETITIVE ENABLERS IN ENGINEERING DESIGN

3.1 Development methodology and process simulation/execution

A *development methodology* is a comprehensive set of specific engineering rules, methods, and procedures that are used to develop or design systems or products in an industrial environment.

There are some well known and often cited approaches such as VDI 2221 [1] or V-Model [3], which are commonly "applied" in industry though mostly adapted to meet the specific requirements of the industrial area and the needs of the individual company. However, those approaches do not consider the increasing complexity and variety of products arising from the integration of different domains (e.g. mechatronics) and the cumulation of requirements regarding sustainability, life cycle aspects, and product-related services besides the "common" needs defined by costs, time and quality. With respect to the 3rd benchmark criterion (bmc 3) this means that current methodologies do not take into account the different types of engineering approaches and therefore do not support collaboration sufficiently. Furthermore, development methodologies mostly focus on phases and the outcome (products, services, software, systems), but not on the engineers and organizations applying them. This means that an individual adaption of the methodical procedures is not possible and not even intended. Accordingly, appropriate methods need to be developed that consider the collaboration of a heterogeneous network of product developers, representing different domains, life cycle phases and companies and characterized by different cultures and individual backgrounds.

Additionally, the traditional engineering methodologies as described in [1], [2] and [3] hardly take into account potentials offered by information technologies since at the time of development of those methodologies computers were about to be developed or just set out to conquer the engineering world. However, information technologies and specific application systems are a prerequisite to avoid physical prototypes reflecting the first benchmark criterion (bmc 1). Also, the general engineering methodologies do not specifically aim at reducing physical prototypes. As a consequence each company has to invest its own logic, considerations and efforts to use design approaches and verified computer models and to adjust virtual prototyping processes to obtain physical prototype reductions. Therefore, academic researcher should use more intensively the opportunity to develop more suitable development methodologies with the direct integration of computer technologies. This, however, will make it indispensable to establish consistent product models for the different conceptual layers of design methodology (requirements, product ideas, system and design layout, embodiment design).

Consistent computer supported design methodology deployment today is still limited by the necessity to permanently convert data between different application systems or database systems. Furthermore, engineers need method and process assistance by intelligent assistant systems. According to the 2nd and the 5th benchmarking criteria (bmc 2, bmc 5) such lack of intelligent method and process assistance makes it difficult to offer a working environment both tailored to the needs of the designer and adopted to the current process state and product maturity. To realize the potentials of IT systems it is necessary to organize the product development process appropriately and to allow for flexibility that enables an adjustment to these objectives.

As stated above, engineering design involves many stakeholders from different domains. To control an interdisciplinary development process it is necessary to handle versatile knowledge of various domains which need to be represented in IT applications appropriately. Development methodologies will only be able to fully enable the 2nd ("*task oriented information and knowledge*") and 6th (*"supporting life cycle views"*) benchmarking criteria if appropriate information management solutions are available to help controlling the way of generating and using information (please compare the next section).

The combined methodology of business processes, process management, project management and systems engineering could have significant potential for several benchmark criteria. Today, however, with respect to bmc 4 ("*robust decision making"*) engineering development methodologies and project management are not yet correlated. Considering project management taking the lead of product development projects the deployed development methodologies need to be adjustable in order to synchronize project and engineering progression.

Customers increasingly ask for complete solutions instead of single products. While services offered for specific products are usually developed separately - often even after completing the product development - the integrated development of products and services is pursued to realize added value and new functionality, cp. [4]. Appropriate VPC solutions to develop Product Service Systems (PSS) and value co-creation need to be able to compare PSS variants, to support collaboration and to deploy distributed decision making according to the 3rd benchmarking criterion *("ensuring best possible collaboration"*).

The changing of global conditions with respect to economy, ecology and socialization have strong influence on the procedural approach of creating industrial products and require an adaption of organizational, methodical and technical aspects. Actually, this addresses the 2nd, 3rd and 6th benchmarking criteria. For the development and creation of sustainable products in general and energy efficient products in particular both the number of people involved in the development process and the information amount to be processed increase significantly. The persons involved need to be supported to ensure a best suitable collaboration. The information and knowledge have to be offered according to task and context. The expanding area of responsibilities of a company for its product, not stopping after the product delivery, makes the companies taking into account life cycle aspects by applying design methodologies for life cycle creation, modeling, management and evaluation.

In addition to generically deployed development methods that provide a kind of overall procedural framework there exist also a range of specific design methods which need to be integrated into the higher design process flow. The range of those methods starts from general procedures for change management, requirements engineering and complexity management, up to specific design methods in CAD system templates or other IT wizards. The later ones represent particular company knowledge and support specific development tasks and solutions. Such approaches mainly address the 2nd benchmarking criterion (bmc 2) by offering task and context oriented information and knowledge.

Concluding intermediately with respect to development methodology and engineering design processes, the analysis reveals that the process itself and its deployed methodologies are key to improve the three aspects of engineering design competition. Since research is still dominantly focused on the "traditional" development methodologies, changes of boundary conditions require changes in mindsets and the development of solutions that meet Virtual Product Creation requirements.

Process description, simulation and controlling are crucial factors for corporate success in product development [5]. However, the product development activities become increasingly complex as explained in the first section. Therefore, the active planning, optimization and adaptive execution of development processes become ever more important. Modeling and simulation of development processes provides a powerful approach to meet these objectives and addresses bmc 8 perfectly.

However, product development processes demand modeling and simulation according to specific terms and conditions. They are characterized by creative elements and more uncertainty than conventional business processes. Unpredictable obstacles and problems frequently require the adjustment of the development plan during the development process. Moreover, product development processes are determined to a great extent by iteration loops. In order to meet these requirements, a tool for a goal-oriented modeling and simulation has to be able to map the characteristics of product development processes mentioned above. Particularly, the stochastic behavior has to be represented.

Process simulation will support ensuring best suitable collaboration (3rd bmc) and enabling robust and transparent decision making (4th bmc) if the following prerequisites are met: (a) representation of aspects and parameters that influence collaboration and decision making, (b) project management characteristics.

Another aspect of the 4th bmc refers to the development process itself. One objective of product development process modeling is to create a predictive model. This model improves managerial decision making and optimizes process predictability [6]. Processes can be defined that are more robust in case of changing conditions. Current problems here are the difficulties and high efforts in analyzing processes and generating appropriate and usable process models.

For process planning the product development process is modeled and analyzed prior to its execution. To realize fast benefits interest is directed towards time to market, cost, and quality. Considering further evaluation criteria such as the environmental impact of the development process itself is possible. In any case the model has to provide the ability to point out the effects of process adjustment by simulation. Common 'adjusting knobs' are improvement of human resources, changes in organizational aspects, and the use and enhancement of the capabilities of information technology [7]. Accordingly, process simulation can be applied to evaluate and optimize development processes with respect to bmc 5, bmc 6 and bmc 7 as well. However, it is necessary to represent and implement the specific characteristics of the real process in the simulation model. Most companies have not yet seriously started to invest into such process modeling capabilities.

Some of the issues mentioned above have been investigated in VPC research projects and first results have been achieved. For instance in the joint research project MIKADO solutions are being developed to support the development of mechatronical products by improving the coordination and adaptation of mechanical, electronical and software development processes and by systematically extending and integrating approaches and tools from these three domains. The solutions comprise a systematic approach for designing and evaluating mechatronical development processes using predefined reference processes and a software tool for modeling and simulating multidiscipline development processes. New modeling and simulation features allow for a more precise prediction of real process behavior and more reliable identification of possible flaws in the process design.

3.2 Context appropriate PLM Information Management (authoring and consumption)

Product Lifecycle Information is crucial to virtual product development and to the 1st benchmark criterion, avoidance of physical prototypes. Avoiding one single physical object leads to generating a myriad of information objects. The integration of a virtual prototype requires the incorporation of a high number of different data elements and cannot carry information the way a physical prototype can. This is why information management is essential already today and has to cope with additional challenges in the future.

With regards to the other seven benchmark criteria, many shortcomings and opportunities exist within the technologies of Virtual Product Creation (VPC) concerning context appropriate Product Lifecycle Management (PLM). Especially the 2nd and the 4th benchmark criteria are not covered by industry available VPC solutions and are also mostly out of scope in today's research activities. Information is not provided context oriented, but rather all at once. Robust and transparent decision making is therefore not yet possible.

Many efforts are under way in the field of benchmark number 3 (*"engineering collaboration")*. As a result a range of semi-functional collaboration solutions are already available within commercial software products, or have been investigated scientifically. Recent research work has been conducted by Gärtner [8] and Langenberg [9] in the Ad-Hoc-Collaboration project and in the CoVes project. Market-ready and basically functional software applications are for example PTC CoCreate® and Dassault Systèmes Enovia® 3D live Collaborative Review. The collaboration in large project volumes is not yet satisfying. Such solutions require better reduced and context appropriate information provision, as well as possibilities to alter 3D models in the manner of computer aided design applications.

Partial solutions exist for benchmark criteria 5, 6 and 7. Whereas the provision of creative, individual adaptable and intuitive working environment is being heavily investigated by human factors research activities in many industrial fields, the focus on product development environments is still comparatively low. Product Lifecycle Management is meanwhile a popular discipline in IT technology and underlines that extended lifecycle views represent a key research are with widespread approaches from science and industry. The next necessary step is a context appropriate lifecycle view, which provides relevant information for different life cycle steps adapted to the requirements of the specific step. Heavily investigated in the scientific world, but not very much implemented in industrial solutions yet, is the 7th benchmark criterion 'Steady maintenance and extension of competence'. Even if a lot of academic research has been conducted in the field of knowledge and competence management, also focused on product development contexts, there is no serious assistance system available on the market. Current solutions such as NX™ Knowledge Fusion, CATIA® Knowledge Expert or CATIA® Knowledge Advisor, are an approach of knowledge management, focused on process knowledge and support in particular development questions by separating expert knowledge from experts and storing it in databases. Competence, though, cannot be separated from the individual. Competence management aims at the development of personal qualifications and experiences of product developers. The integration of competence management processes into the product development process is still not satisfying. To provide information in an appropriate way, the competence of the information consumer, that is the engineer, is one of the most relevant context parameters. Intensive research in the concern of competence management in product development processes has been done by Strebel [10] and further elaborated by Stöckert et al. [11].

Due to the steady ongoing development of information systems, the amount of information created is literally snowballing. But even if increasing amounts of information throughout the product lifecycle becomes available for product designers, engineers, marketing personnel and others, they are not becoming better informed. The growing abundance of information is not properly structured, edited and visualized. Every part of information, every document, every product model and every working instruction is available at any point in time and without sensitivity to the context. This information overload actually becomes manifest as a lack of information.

Context sensitivity research has been done throughout the last decade. Current approaches include weighted links, well-known from Amazon.com® book recommendations, implicit feedback mechanisms [12], complex adaptive systems (CAS) in form of multi-agent solutions [13] and information retrieval based on quantum theory [14]. Another well-established utilization is context sensitive user help within software applications. An adoption to the industrial field of product development and product development software systems has not yet taken place. One main reason is the abundance of different, non-standardized processes in product development which is strongly connected to the lack of consistent information classifications in this industry. Even if the standardization of innovative work is not to be expected, certain information classifications for virtual product creation are possible and already overdue. The possibility to adopt these techniques in a functional way may not be anticipated with levity. Serious, extensive research still has to be conducted.

What has to be done to comply with the mentioned benchmark criteria? To secure the 4th benchmark criterion, robust and transparent decision making, information has to be provided context sensitive. Five dimensions are necessary to fully describe a context in product development:

- Domain
- Product
- Tool
- Process
- Person

Domain and product are related and overlapping dimensions, as domain is related to product groups like automotive industry, aviation industry or plant engineering and construction. Products are rather single components and can belong to more than only one domain. Attributes of the product dimension are material, production technique and quality requirements in general.

Different tools have different user interfaces and address different working foci. Information, regardless of the information source, has to be integrated in the according environment and is therefore another relevant dimension for context appropriate information management. Tool and process are again dimensions which interact. Project milestones, development maturity and underlying process model reflect the process dimension.

Person related attributes contain knowledge and competence of the product development subject in general and, more specific, experience with situations similar to the current task. Also widely varying between individuals are cognitive models and the resulting ways of learning and information reception. Striking examples are the theoretical learner who gathers information in terms of formulas and concepts, whereas the practical learner needs to have tangible examples to get the idea. These and many more individual preferences need to be met to comply with the 5th benchmark criterion, creative, individually adaptable and intuitive working environments.

Again five points have to be taken into account when talking about context sensitive Product Lifecycle Information:

1. Generation
2. Classification
3. Embedding
4. Provision (Visualization)
5. Controlling

To be able to properly prepare information for context appropriate usage, these five steps have to be systematically planned and executed. Information generation sets the foundation of information management and has therefore by far the broadest impact on later phases. In the moment of creation, a lot of meta information is available that has to be documented to simplify later information reception and embedding processes. Examples are the context of information creation regarding decision-making processes, possible addressees of the created information and dependencies to other information objects. All these information elements have to be laboriously recaptured if they are not systematically documented in the first place. Many parts of this information capturing can be processed automatically with today's state of the art technology; some are rather to be determined by interaction with the information draftsman.

Information classification has to be conducted for additionally generated information as well as for already existing information sets. Present information objects are instrumental in establishing classification structures since they show the actual sources and drains of information in everyday business. This leads to two different ways of classification: ontologies and weighted relationships.

Whereas ontologies, i.e. semantic links, claim to be ubiquitous, weighted relationships are a representation of factual connections between information elements. Both ways of classification are necessary to provide information only in the correct context and not by indiscriminate all-round distribution.

Embedding requested information in specific product development contexts is the next step. Therefore, the working context has to be identified by the VPC tool automatically or with the cooperation of the product developer. Learning systems are able to capture contexts according to the beforehand mentioned weighted relationship classification. This step is the core of context appropriate information management since the problem of context sensitivity has to be tackled here, and links closely to the following. Both aim at the target of selected dissemination of information (SDI). Not every possible piece of information is appropriate in every context but only the one needed in terms of project milestone, precognition, relevance and all other attributes of the five context dimensions. Eventually, this approach will lead us from pull to push strategy. Information will not be requested, but provided.

Provision is the next step after creation, classification and embedding information in the appropriate context. Information from different sources has to be integrated into single work environments and the according surrounding conditions. Appropriate visualization, adaptable to individual working environments and personal preferences, supports the fulfillment of the 2nd and 5th benchmark criterion, task and context oriented information and knowledge in creative, individually adaptable and intuitive working environments. Extended lifecycle views, requested in the 6th benchmark criterion, are part of this step, too.

Last but not least, and regularly not taken into account, is the need for controlling in information management. Besides information quality, there is also an issue concerning efficiency. As it is no end in itself, there is always a relation between effort and benefit of information management, which is more tangible, the relation between complexity and degree of assistance. Determining factors for this ratio are the number of cooperating parties, the depth of classification structure and the frequency of use of information structures. As there will always be the necessity for somebody to clean up information libraries, the resulting amount of administrative tasks largely influence this ration, too. Even if these fundamental coherences have been identified, information controlling in product development is still far behind other techniques in product development and far behind controlling in other disciplines like manufacturing, sales or logistics.

Some of the mentioned issues are already being investigated at the chair of Industrial Information Technology of the Berlin Institute of Technology and at the Fraunhofer IPK in research projects and first results have also been achieved:

1. *Ad-Hoc-Collaboration*
   Best possible collaboration environments, as requested in the 3rd benchmark criterion, are the objects of research in the Ad-Hoc-Collaboration project. Particularly with regard to today's outsourcing, reduced vertical integration and multinational design teams, distributed design activities affect product lifecycle quality, time and costs. A functional prototype for collaborative engineering and virtual design reviews has already been implemented. The project has almost been finished, but a renewal proposal to conduct further detailed research activities, based on preliminary achievements, is already in preparation.
2. *ProGRID*
   Spreading and dressing up information to every person, acting at any step of the product lifecycle, becomes more and more a question of computing and communication technologies performance. Especially mathematical and visual simulations are crucial to transform stodgy information into tangible and immersive experiences as well as to predict the behavior of virtual prototypes. The ProGRID project researches the utilization of high-capacity grid computing for virtual engineering purposes.
3. *MIKADO*
   Handling complex, multidisciplinary contexts in product development is extra tricky. Therefore the joint project MIKADO has been started to establish a coherent and integrated systems engineering basis for the development of mechanical, electric and control components as well as software. Cross company information and cooperation models are being developed and implemented in tools to support requirements engineering and the predictability of total system behavior. Main functionalities are virtual validation, testing capabilities and diagnosis procedures.

3.3 Functional product modeling and simulation

The availability of appropriate product modeling and simulation technologies and methods can be regarded as one of the decisive factors in supporting a competitive engineering design performance. It is obvious, that technical advances in these areas particularly contribute to the avoidance of physical prototypes by replacing these with digital counterparts. Although remarkable improvements have been achieved there are a number of aspects which are subject of further development [15].

By now 3D-CAD modeling technologies have achieved a very high application depth and maturity. Existing tools have evolved to versatile but also complex systems. Provided modeling methods as parametric design or templates technology allow rapid changes of parts/assemblies, fast generation of variants and capturing of design knowledge (bmc 7). Created 3D-CAD models serve as the common basis for all engineering processes such as CAE, blue print for CNC Manufacturing as well as the Digital Mock-Up (DMU).

In analogy to the Physical Mock-Up (PMU) the DMU provides a computer-internal product representation which is mainly targeted to avoid mistakes and identify problems of a design [16]. It is noticeable, that current tools such as CATIA® DMU-Navigator or Teamcenter® Visua-lization Mockup predominantly address geometric and spatial validation tasks such as clash detection, interference check, evaluation of space requirements, computation of physical properties, or measurement of distances. Necessary process chains for modeling and generation of used lightweight geometry models are aligned accordingly and recognized robust and highly automated. With respect to criteria 2 and 3, existing integration into PLM-environments assures access to up-to-date models and application depended views.

Integrated methods for the validation of dynamic aspects of a product are only partially tackled yet. Kinematic or ergonomic simulations have been established for example. But mostly the inspection is covered by specialized application dependent simulation tools.

The combination of these tools with other domain-specific simulation or design tools represents today's implementations of a functional Digital Mock-Up, also called Functional Mock-Up (FMU). Via the incorporation mechatronical interactions and a more realistic behavior of virtual products and prototypes can be simulated. Some applications such as LMS Virtual.Lab, Simulia® or MSC SimManager™ already offer full product simulation packages. However, the analysis of product functions is still expensive and it partially lacks integration, which causes several drawbacks such as:

- high effort for model preparation due to manual collection of information,
- delay in the availability of simulation results,
- high effort in the management of simulation data (models, parameters, results),
- multiple generation of product information in different systems and at different levels of detail/abstraction,
- no rapid investigation of product functions,
- cumbersome determination of the fulfillment of requirements by product functions

To overcome these limitations and also to cope requirements caused by the strong demand to validate mechatronical products, new comprehensive and integrative approaches are required. Also the focus will be shifted to a cross-domain design, modeling and simulation of the whole system, whereas a holistic optimization of the component interactions will come to the force. A continuously function oriented approach for engineering design promises to eliminate mentioned drawbacks, but requires to create relationships between requirements, functions and geometry as well as physical properties or even better to aggregate them into one information model. Consequently, new methods for the definition and modeling of functional assemblies need to be provided. Yet disjunctive methods for geometric and abstract modeling have to be joined and aligned. First research directed to a system oriented modeling is actually undertaken.

To fully archive this goal a centralized and seamless data management has to be established not only for geometric information, but also for part properties, simulation models as well as results etc.. Furthermore, the process chain for simulation-model creation needs to be configured, automated and integrated into the product lifecycle management. With these enhancements implemented the essential foundation for coupled cross domain simulation is laid and thus a full behavior model of the digital product can be derived.

This represents the first important step to a real fulfillment of the criterion 1 and also criterion 7 for an improved knowledge capturing. Furthermore Functional Mock-Ups also have to support verification methods related to the benchmark criterion of delivering extended lifecycle views. For example the disassembly simulation of a product needs to regard the fact that components properties change during its life. Recent research work has been conducted with the objective to provide methods of the simulation of product use and the consideration of its influence on form and function as well as their impact on the disassembly process [17].

With respect to support robust and transparent decision making as well as an intuitive working environment new Human-Machine-Interfaces (HMI) are advised for the realization of an intuitive interaction with digital prototypes. Virtual Reality (VR) can support new ways of interaction with digital prototypes, not only by integrating simulation methods, but also with the help of new HMI (Human Machine Interface) techniques. Both can contribute to the acceleration of product development processes and to the improvement of decision making. The goal in using VR is to provide an intuitive and natural work environment for digital prototypes similar to the human interaction with real prototypes. This would enable even responsible management to access to a functional experience within digital supported decision making. Meanwhile, the VR-Technologies have reached a remarkable level of industrial application. Examples of currently applied VR tools are IDO (ICIDO) or DeltaView (Realtime Technologies).

The next development steps are the extension of real time capabilities of computational algorithms as they have an important influence to the interaction between user and digital prototype. Thus, the focus of development is real time methods for interactive dynamic simulation and physically correct deformation simulation. Additionally, haptic interaction methods have to be improved and supplemented by real time collision detection or generation of contact forces for large assemblies.

Several of the above described challenges are already covered by running research projects which are conducted by the chair of Industrial Information Technology of the Berlin Institute of Technology and the division Virtual Product Creation at the Fraunhofer IPK. For instance in the joint research project “AVILUSplus” the topics of PDM/CAx-VR-Integration for functional validation, real time physical simulation of flexible parts, and tangible interaction in Virtual Environments are addressed.

4 CONCLUSIONS AND PROSPECTS

The chart in figure 1 gives a final overview of the relations of VPC technologies and solutions with respect to the benchmark criteria concerning engineering design competition according to the current research assessments. It shows a qualitative estimation of the current state of VPC technologies deployment meeting the benchmarking criteria. Looking ahead, it also shows the tendency of potentials for future research and development activities with a perspective of the next five years.

With respect to *development methodology and process simulation* the following characteristics exist: for the 2nd and 7th benchmarking criteria only implicit but no explicit support yet exists. This means, that executing a process always implies a context for information relevance and competence orientation. Additional potential exist in doing it more actively and explicitly. High potentials have been identified for the 3rd, 4th and 8th criterion. In particular, an active modeling of product development processes and the application of these models for process optimization purposes, for instance by process simulation, will offer great benefits.

Concerning the research field of *information management*, high potential is evident for the 2nd, 3rd, 6th and 7th criterion. Information management is not only a contributor in these cases, but an active enabler to further developments and innovations.

Significant potential in the area of *functional product modeling and simulation* exists related to criteria 1, 5 and 6. Although the level of maturity of single applicable technologies is already high, a further development of Functional Mock-Up frameworks, validation of lifecycle aspects and Virtual Reality enabling new HMI will tap the full potential.

Benchmark Criteria	VPC technologies and solutions					
	Methodology and Processes		Information Management		Modelling and Simulation	
	As Is	Potential	As Is	Potential	As Is	Potential
1 no pysical prototypes	o	↗	+	↗	+	↑
2 context oriented information	+	↗	o	↑	+	↗
3 best suitable collaboration	+	↑	+	↑	+	↗
4 robust decision making	o	↑	o	↗	+	↗
5 intuitive work environment	o	→	o	↗	+	↑
6 life cycle views	+	↗	+	↑	o	↑
7 competence maintenance	+	↗	o	↑	+	↗
8 development process planning	o	↑	+	↗	o	→

++ strong influence ↑ high potentials to attain bmc
+ medium influence ↗ medium potentials to attain bmc
o low or no influence → low potentials to attain bmc

Figure 1: Current state and potentials of VPC technologies with respect to benchmark criteria (bmc)

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